DYNAMICS STUDY OF ELECTROMECHANICAL ACTUATOR OF AN IMPLANTABLE CENTRIFUGAL BLOOD PUMP USING A SIMULATION STATE-SPACE MODEL

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Abstract. *The permanent magnet brushless direct current motor (BLDC), have been the main component in most of the Ventricular Assist Devices (VAD) development. An implantable centrifugal blood pump is being studied at the Institute Dante Pazzanese of Cardiology (IDPC) as Ventricular Assist Device (VAD) to assist patients with cardiovascular diseases. Its use in patients with heart disease is indicated as a bridge to cardiac transplantation, as a bridge to the patient's recovery and as a bridge for gene therapy. Among the characteristics of the BLDC motors used in implantable pumps, there is the absence of brushes, which allows avoiding the inevitable detrition observed in other motors, and intolerable in VAD's. Thus, improvements can be studied in the motor controller and they are required to obtain a reliable dynamic model. Toolbox SimPowerSystems software package (SimPowerSystems, MATLAB, Simulink) was used to study the dynamic system. The electromagnetic and mechanical parts of the motor were represented by a block Permant Magnet Synchronous Machine (PMSM) with a trapezoidal Back Electromotive Force (BEMF) signal. The block implements the differential equations for the motor through a state-space model. A Proportional Integral controller (PI) was used for the simulations. Electromagnetic and mechanical parameters were proposed in simulations that showed satisfactory results when compared with results of tests conducted earlier in the actuator. In future works, the results presented in this work will be used to refine the motor model for this application. Thus, it will allow reliable simulations of new proposed drivers.*

Keywords*: Implantable Centrifugal Blood Pump, Ventricular Assist Device, Permanent Magnet Brushless DC, BLDC, dynamic model.*

1. INTRODUCTION

The brushless motors, BLDC, have been the main component in the development of most of the Ventricular Assist Device (VAD). Among the characteristics of the BLDC used in implantable pumps, there is the absence of brushes, which allows avoiding the inevitable detrition observed in other motors, and intolerable in VAD's (Bock *et al*, 2008). An implantable centrifugal blood pump is being studied at the Institute Dante Pazzanese Cardiology - IDPC as DAV to assist patients with cardiovascular diseases, showed in Fig. 1. This device can be divided into: blood pump continuous flow centrifuge, an electric motor BLDC, a controller to drive the motor and a battery system. Centrifugal pumps represent the majority of research currently developed, which allows operation at lower speeds than the continuous flow axial pumps; obtain lower rates of hemolysis, ie, less damage to blood elements, have dimensions compatible with the total implanted and reach the estimated life together in support of 2 years (Bock *et al*, 2010; Nose, 1998).

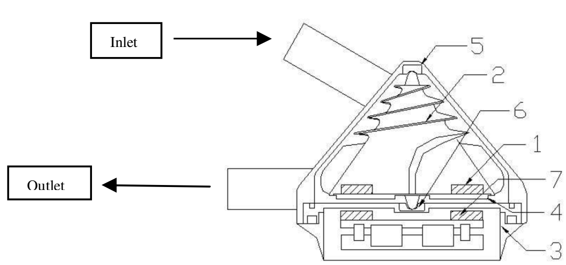

Figure 1. Implantable Centrifugal Blood Pump and actuator. 1) magnet coupling in pump rotor; 2) pump rotor; 3) actuator (BLDC motor); 4) scraper to move the blood; 5) bearing top; 6)bearing bottom; and 7) magnet coupling in BLDC motor (Bock *et al*, 2010).

The electric motor three-phase brushless motor is a synchronous permanent magnet on the rotor and coils on the stator located, usually star connected with inverter control for bridge-type H (Fonseca, 2003; Hsieh and Liao, 2010). The operation of a BLDC is accomplished through strategic switching of the coils, as well as in a stepper motor. The switching is performed by a circuit that supplies current to the motor coils as a function of rotor position. The phase current of a BLDC, usually rectangular is synchronized with the Back Electromotive Force (BEMF) to produce maximum torque and constant speed, with the trapezoidal BEMF, which is the main characteristic of control (Fonseca, 2003; Shao, 2003).

The dynamic model is necessary to study transients of the motor drive system and steady state. The instantaneous currents are crucial for power computation and electromagnetic torque is of importance in evaluating the drive system performance. These features become a significant factor in appliances as DAV, different of industrial appliances that may not be significance (Krishnan, 2010).

This paper has been divided into two main parts; the first consist on shows the mathematical modeling that the Simulink block used to represent BLDC motor, and second part describe the virtual implementation, with help of Mallab / Simulink, blocks diagram to represent the electromechanical actuator. However, the main contribution that this paper wants to show is a dynamic model to start studies about the current control.

2. SYSTEM EQUATIONS

A three-phase BLDC connected to an inverter with its dc supply is shown in Fig. 2. This model is based on the assumptions that the stator resistances of all the windings are equal, self and mutual inductances are constant, the induced currents in the rotor due to stator harmonic fields are neglected, and iron and stray losses are also neglected (Krishnan, 2010). Equation (1) expressed the voltage equations of the three phases.

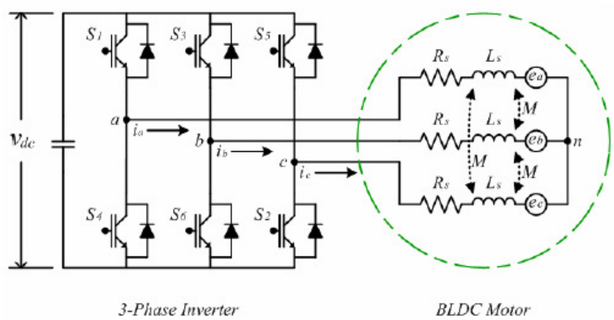

Figure 2. Block diagram BLDC motor drive (Kim, 2008).

$$\begin{bmatrix} Vas \\ Vbs \\ Vcs \end{bmatrix} = R_s * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \mathbf{p} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (1)$$

The generated electromagnetic torque is given by

$$T_e = (E_a I_a + E_b I_b + E_c I_c)/\omega \ \ [N.m] \quad (2)$$

Electrical rotor speed and position are related by

$$d\theta /dt = (P/2)* \omega \quad (3)$$

Also, value torque.

$$J(d\omega /dt) + B\omega = T_e - T_l \quad (4)$$

Where V_{as}, V_{bs} and V_{cs} are phase voltage. R_s is a stator resistance. I_a, I_b and I_c are phase current. L is a stator inductance. M is a mutual inductance. E_a, E_b and E_c are back-electromotive force (BEMF). ω is a mechanical angular velocity. T_e is an electromagnetic torque. θ is an angular position. P is the number of de poles. J is a moment of inertia. B is a friction coefficient. T_l is a load torque.

3. SIMULINK MODEL

The model implemented in MATLAB/SIMULINK used blocks of the SimPowerSystems toolbox. The BLDC was simulated with a block of Permanent Magnet Synchronous Machine (PMSM) with a trapezoidal back electromotive force (BEMF) signal. Electrical and mechanical parts of the machine are represented by a second-order state-space model (Matlab, 2010).

The BLDC is connected to an inverter and supplied by a variable source of Direct Current (DC). This source is adjusted by a Proportional Integral (PI) control with feedback of motor speed.

A measures block was included to estimate stator current, i.e., power of BLDC.

Figure 3 show block diagram to study the dynamic of the actuator electromechanical of an implantable centrifugal blood pump.

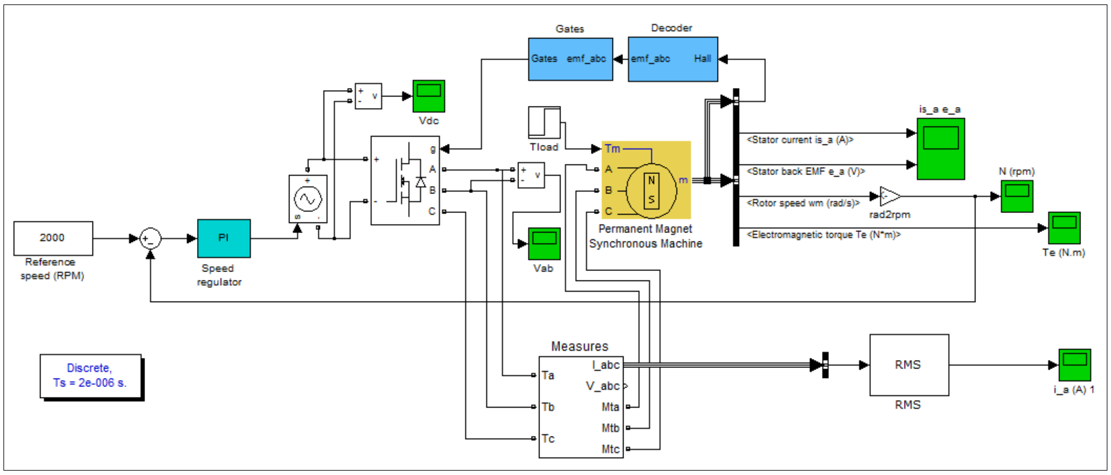

Figure 3. Block Diagram BLDC

4. RESULTS

In this section, we are going to verify the operation of the simulation of block diagram showed. Electromagnetic and mechanical parameters were proposed, according Table 1 (Maxxon, 2008).

The parameter of the load torque has been obtained from tests done previously (Bock, 2007; Bock *et al*., 2008; Leão *et al*., 2009; Leão *et al*., 2010). Rotations used in the simulations are typical rotations found in ventricular assist devices that used centrifugal pumps to care of patients (Bock, 2007; Nose, 1998). These considerations we have: load torque between 0.0013 and 8.49 mNm to speed 1500 rpm; and 0.00116 and 15.9 mNm to speed 2000 rpm.

Table 1. Motor parameters

Manufacturer	Maxxon Motors
Model	EC 45 flat
Nominal Voltage	12V
Terminal resistance phase to phase	1.4 Ω
Terminal inductance phase to phase	0.56 mH
Torque constant	25.5 mNm/A
Speed constant	374 rpm/V
Speed / torque gradient	20.6 rpm/mNm
Mechanical time constant	19.9 ms
Rotor inertia	92.5 gcm^2

To avoid too many voltage, current, speed and torque waveform presentation, only some results are selected as shown in Figs 4 – 7 for the mechanical speed of the rotor, the sator current phase A and BEMF phase A, the electromagnetic torque, and the motor's current, respectively. Simulation condition chosen to show as follows: speed 2000 rpm and load torque 0.0159 Nm because it is maximum speed and load torque.

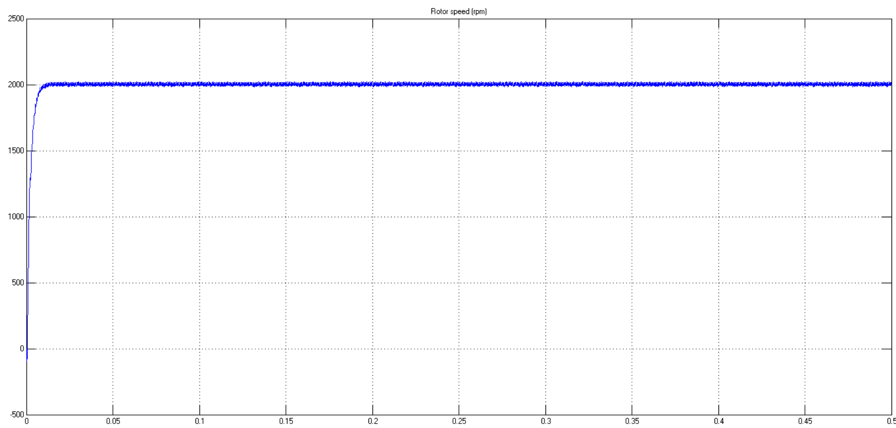

Figure 4. Graphic Speed: transient response with adjust to 2000 rpm.

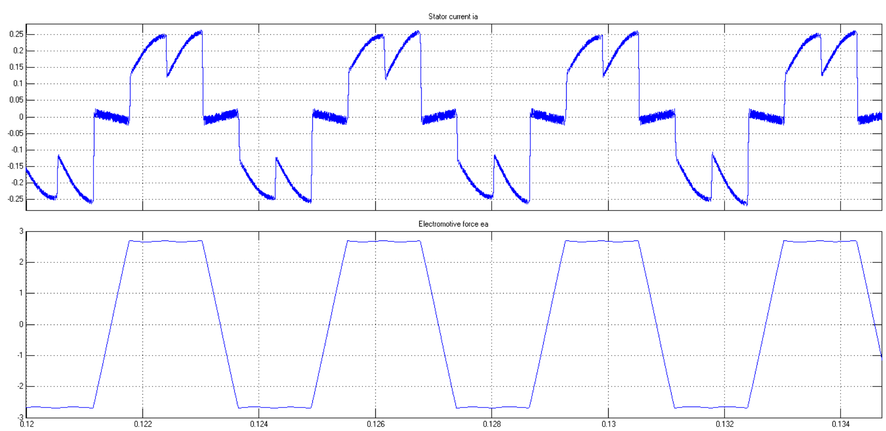

Figure 5. Graphic Stator current and back electromotive force (BEMF) to 2000 rpm.

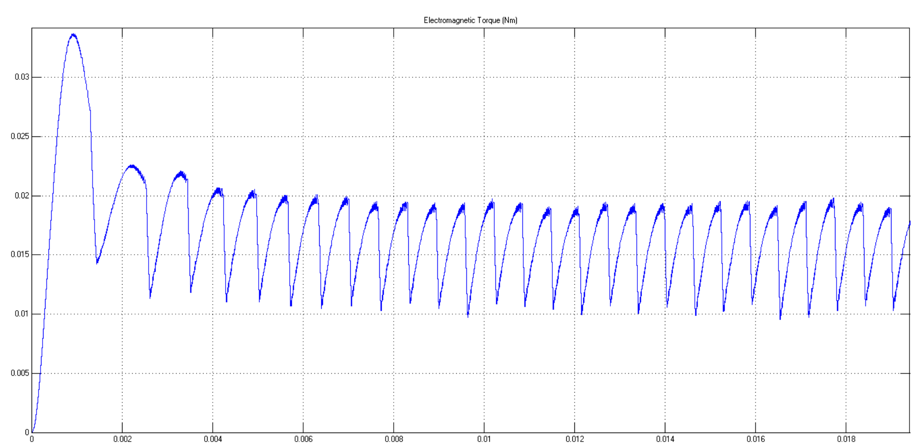

Figure 6. Graphic Electromagnetic torque: adjusted to 0.0159 Nm load torque.

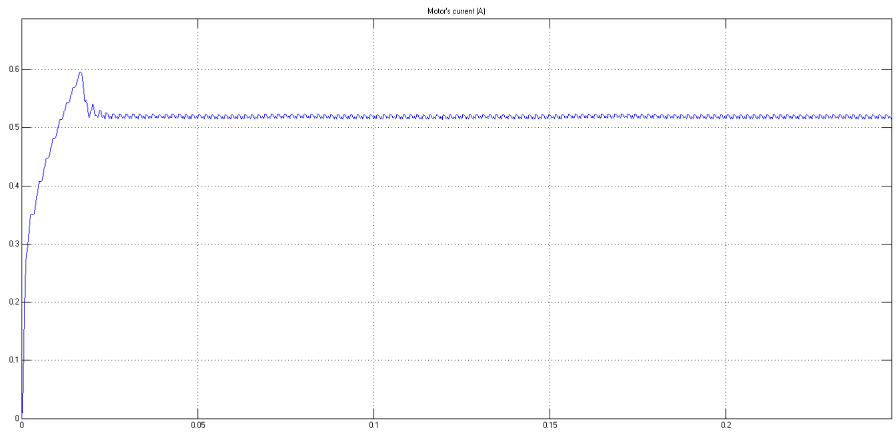

Figure 7. Graphic Motor's current: transient response.

The results as shown in Figs 4 – 7 show that parameters waveform electrical and mechanical are according with the literature (Krishnan, 2010). From Fig. 4, the motor speed stabilizes in 0.012 sec with 3% overshoot, these features indicates that PI controller is satisfactory. From Fig. 7, the motor's current show values close to those values found on the manufacturer's catalog.

Figure 8 shows torque-power curve. The previously test values were obtained from a similar actuator. It should be emphasized that the actuator have constructive differences (electromagnetic and mechanical) significant.

The estimated power for a ventricular assist device (VAD) is around 10 W (Bock, 2007). When submitted to actual loads, the model shows power values compatible with the application of a ventricular assist device (VAD), as shown in Fig. 8.

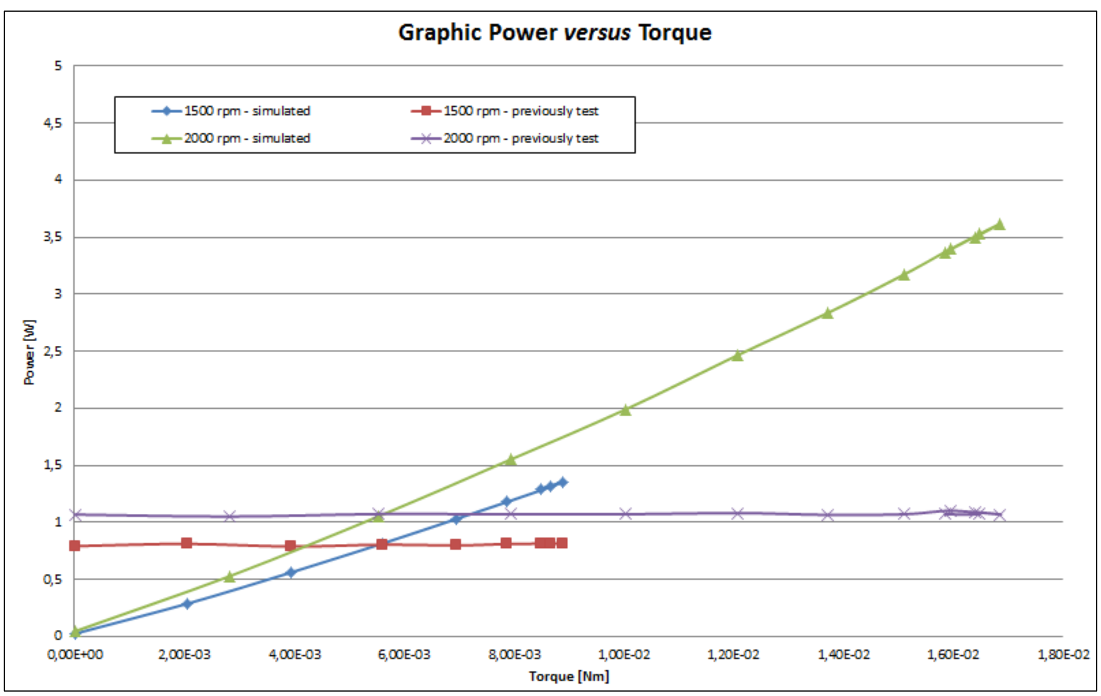

Figure 8. Graphic Power

The difference between waveform simulated and previously test waveform, as shown in Fig. 8, it is justified because the simulation uses the PI control by adjusting a variable DC source and similar actuator controller uses Pulse Width Modulation (PWM) to regulate speed.

5. CONCLUSION

In this paper, the dynamic model was presented to represent an electromechanical actuator of an implantable centrifugal blood pump. This dynamic model allows to start stydies of controller and to improve modeling.

In comparison with a similar actuator, we can observe that the characteristic curve differs according to the type of control applied, suggesting that an improvement in the model could be implemented with a PWM control. Furthermore, power values suggests that similar actuator control is more efficient.

Future research must be developed to improve the dynamic model relative to control, for better power values. Motor dynamometer tests should be conducted with the aim to validate the model dynamic.

6. REFERENCES

Bock, E. G. P., 2007, "Projeto, Construção e Testes de Desempenho "In Vitro" de uma Bomba de Sangue Centrífuga Implantável", dissertação de mestrado, Campinas, Universidade Estadual de Campinas – Unicamp.

Bock, E. et al., 2008, "New Centrifugal Blood PumpWith Dual Impeller and Double Pivot Bearing System:Wear Evaluation in Bearing System, Performance Tests, and Preliminary Hemolysis Tests", Artificial Organs 32(4):329–333.

Bock, E., et al., 2010, "Introductory tests to in vivo evaluation: Magnetic coupling influence in motor controller". ASAIO Journal 56 (2):128.

Fonseca, J.W.G., 2003, "Técnica "Sensorless" para o Acionamento de Motores "Brushless DC" Aplicados em Circulação Artificial", Master Thesis, ITA.

Hsieh, M. and Liao, H., 2010, "A Wide Speed Range Sensorless Control Technique of Brushless DC Motors for Eletric Propulsors", Journal of Marine Science and Technology, Vol. 18, No. 5, pp. 735-745.

Kim, T-S, Park, B-G, Lee, D-M, Ryu, J-S, Hyun, D-S, 2008, "A New Approach to Sensorless Control Method for Brushless DC Motors", International Journal of Control, Automation, and Systems, vol. 6, no. 4, pp. 477-487.

Krishnan, R., 2010, "Permanent Magnet Synchronous and Brushless DC Motor Drives", Ed. CRC Press, Virginia, USA, 457 – 495 p.

Leão, T.F., Fonseca, J.W.G., Andrade, A.J.P., Bock, E.G.P., 2009, "Desempenho "In Vitro" do atuador eletromecânico da bomba de sangue centrífuga implantável", Proceedings of 2th Encontro Nacional de Engenharia Biomecânica, Santa Catarina, Brazil.

Leão, T.F., Antunes, P., Chabu, I., Fonseca, J., Andrade, A., Campo, A., Bock, E., 2010, "Desenvolvimento do controlador e da lógica de controle do motor da bomba de sangue centrífuga implantável", 1th Encontro sobre sistemas propulsores eletromagnéticos implantáveis para Dispositivos de Assistência Circulatória sanguínea uni e biventricular ou Coração Artificial – Projeto Temático FAPESP, EPUSP, São Paulo, Brazil.

Matlab, 2010. "Permanent Magnet Synchronous Machine", Mathworks, 23 Nov 2010. <http://www.mathworks.com>.

Maxxon, 2008, "Data motor EC45 flat", p. 202.

Nosé Y., 1998, "Design and Development Strategy for the Rotary Blood Pump". Artif Organs 22:438-446.

Shao, J., 2003, "Direct Back EMF Detection Method for Sensorless Brushless DC (BLDC) Motor Drives", Master Thesis, Virginia Polytechnic Institute.

7. RESPONSIBILITY NOTICE

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